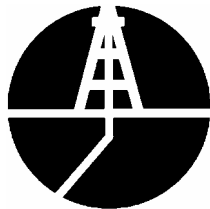


**MMS Project**  
**Long-Term Integrity of Deepwater Cement**  
**Systems Under Stress/Compaction Conditions**

**Energy Analysis Spreadsheet Annotation**

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## Introduction

The purpose of this document is to explain the data analysis method and annotate the MMS Energy Analysis spreadsheet “MMS Ph 1 Energy Analysis.xls”. The results of the Annular Seal testing were analyzed by utilizing an energy approach, in which the energy applied to the pipe / cement / formation system constitutes the mechanism of failure. Resisting the applied energy are the mechanical properties pipe, cement, and formation, operating as a system. This methodology is essentially a macro approach, intended to eventually understand the relative effects of both production heat up as well as pressure application on the integrity of the cement sheath. By analyzing the data in terms of energy applied to the system and resisted by the system, disparate forms of energy can be correlated and understood.

## Analysis Methodology

Test methodology is fully explained in the various MMS Reports previously published. For the purpose of analysis, two dimensionless variables are defined to quantify the energy applied to the system as well as how the system resists the energy input. When plotted against each other, calculated laboratory Energy Application factor (E1A) and Energy Resistance factor (E1R) correlate to a power equation ( $E1R = X * E1A^Y$ ). The values constitute a failure curve; E1A:E1R values below the curve are more likely to fail due to the energy application, and values above the curve are less likely to fail. A point is also plotted for a field condition to show the relationship between the field condition and the lab-generated cement failure.

Discussion and rationale for the dimensionless variables E1A and E1R are as follows. It is important to note that these factors were generated with a very limited number of data points. Further refinement is possible in the future as Phase 2 progresses and more data is generated.

$$E1A = \frac{\text{Energy} * \text{Hole Radius}}{\text{Mass cmt} * \text{Pipe Steel Area}}$$

E1A is a measure of the intensity of the loading on the cement sheath. The factor is directly proportional to the Energy applied to the system as well as the Hole Radius, so those variables appear in the numerator. The loading intensity is inversely proportional to the mass of the cement as well as the Cross-Sectional area of the steel in the pipe. The Hole Radius seeks to quantify the effect of larger-diameter wells in terms of the increased loading associated with the pressure inside the pipe. On the other hand, some of the energy is consumed by the steel pipe before it can transfer load to the cement, so the amount of steel is located in the denominator.

$$E1R = \frac{Ff * \text{Volume cmt} * \text{Tensile Strength cmt}}{\text{Energy} * \text{Young's Modulus cmt} * \text{Anelastic Strain}}$$



E1R is a measurement of the ability of the cement and formation system to resist the applied energy. Terms in the variable include:

- Ff: Formation Factor, defined by Formation Young's Modulus / 2,000,000. This is a measure of the competence of the formation. The harder the formation, the better "backup" it lends to the cement sheath, and the less likely the cement is to fail under applied energy.
- Cement Characteristics:
  - Volume: As the volume of cement is increased, the ability of the sheath to resist failure increases.
  - Tensile Strength: The higher the tensile strength, the more it is able to resist hoop stresses imposed by internal pipe loading
  - Young's Modulus: The more brittle the cement (higher Young's Modulus), the more likely it is to crack under internal pipe loading. For this reason, this factor is contained in the denominator.
  - Anelastic Strain: This factor constitutes permanent deformation under cycling stress well below ultimate strength. The slope of the linear fit is used as opposed to a discrete value, because the Anelastic Strain value varies with the number of cycles. The factor is in the denominator because a zero slope would be consistent with a material that does not exhibit this behavior, such as steel. The higher the slope of the linear regression line, the less the ability of the cement to resist repeated load applications.
- Energy: Energy applied to the system is located in the denominator because higher energy levels decrease the ability of the system to remain intact over time

For the lab data, the correlation between E1A and E1R, using the energy at which failure of the cement sheath is detected by the presence of gas flow, is:

$$E1R = 8.02 \times 10^6 * E1A^{2.1304}$$

This line constitutes the failure line, because it was created by E1A and E1R pairs generated at the point of failure. E1A and E1R points for a given situation that fall below the line indicate a likely failure of the cement sheath; points above the line indicate cement sheath integrity. As the number of data points that were generated is relatively low, the line does not represent an absolute failure / non-failure demarcation. Confidence increases with distance from the line, either above or below.

## **Spreadsheet Operation and Scaleup**

The spreadsheet allows the user to input actual well conditions (hole size, pipe OD and ID, and cemented interval), as well as cement and formation qualitative identifiers. The cements tested included Type 1 and Latex slurries mixed at 15.6 lb/gal, and Bead and Foam slurries mixed at 12.0 lb/gal. Formation types include Hard (represented in the test by steel pipe, YM > 2,000,000 psi), Intermediate (represented by PVC pipe, YM



approximately 500,000 psi), and Soft (unconsolidated sand pack, YM approx 200 psi). Additional user inputs include a pressure application schedule, in which the user selects the number of times that the well is subjected to various levels of internal pressure.

All user-input cells are denoted by **Bold Red** font, and only those cells may be altered. The spreadsheet calculates E1A and E1B for the field condition, and plots the single field point on a graph with the curve fit lab failure line. Two identical graphs are provided – one immediately below the pressure application data and one a separate tab of the workbook. The graph presented on the calculation tab is useful for seeing the effects of changes to well conditions, or cement and formation type quickly.

## Next Steps

The analysis shows promising trends in dimensionless analysis of cement sheath loading, but is based on very few data points. The same correlation described here and presented in the spreadsheet is valid for energy input in the form of temperature, but more precise measurements and additional data points are required for confirmation. Additional cement and formation types will also verify and extend the analysis to a broader range of real-well conditions.